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NUMERICAL SIMULATION OF A
MULTI-COMPARTMENTED GUN MUFFLER
AND COMPARISON WITH EXPERIMENT

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SEPTEMBER 1990

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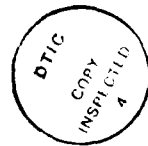
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13. ABSTRACT (Maximum 200 words) The internal flow of a multi-compartmented muffler was investigated both by experiment and simulation to determine the attenuating mechanisms and internal flow of gun mufflers. The muffler, which had approximately nine times the internal volume of the bore and chamber of the gun, was attached to the 25mm M242 cannon. Pressure transducers were inserted at selected locations on the cylinder of the muffler and gun barrel to measure internal pressures. The simulation of the experiment, as implemented on a Cray XMP-48 computer, solved the Euler equations of compressible flow by using the second-order-accurate total-variation-diminishing (TVD) shock-capturing scheme of Harten. The calculation yielded a detailed picture of the flow field, as displayed by pressure and Mach contours. Comparisons of the simulation with experiment showed that some burning of propellant in the muffler chambers was occurring even though the muffler had been purged with nitrogen. Salient features of the muffler internal flow are discussed.				
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I. Introduction

Investigations of mufflers have primarily focused on how noise attenuates with the variation of geometrical parameters. The muffler's attenuation generally increases with its internal volume. Attenuation increases with the number of baffles but only up to a certain value and then decreases thereafter.^{1,2} The attenuation also depends on the length of the inlet chamber, the placement of the baffles, and projectile hole size. The optimum entrance chamber length is in the 6 to 12 caliber range while the projectile hole size should be made only large enough to pass the projectile.

Bixler et al.¹ considered more than one model of muffler operation, including acoustic filter theory,³ Whitham's⁴ model for one-dimensional shock motion in channels of variable area, and one-dimensional shock-wave theory.⁵ The latter theory has been used by other authors^{2,6} to analyze the flow in the entrance chamber of a muffler. Mori et al.⁷ have applied one-dimensional gas dynamics to approximate the flow between baffled chambers whose lengths are much greater than their diameters. Muffler diameters are generally greater than the distance between successive baffles. Even if the chambers were long enough to permit a one-dimensional approximation, these approaches only yield the initial mass flux through the exit hole. As will be seen later, the initial flow values through a well-designed muffler are not directly related to the noise attenuation for the muffler.

If more were known about the noise attenuation mechanisms and internal gas flow in silencers, the design methodology could advance beyond the cut-and-try approach and then prediction methods might be developed for optimizing muffler performance. Although the internal flow processes have not been investigated very thoroughly, it is known that mufflers attenuate noise by reducing the rate of propellant energy being released from the muffler exit hole.^{6,8,9,10} For guns without mufflers, it is assumed that the noise level depends on the peak energy efflux from the muzzle. For guns with mufflers, it is assumed that the noise level depends on the peak energy efflux from the muffler exit hole.

Recently, numerical and experimental approaches¹¹ have been coupled successfully for

¹Bixler, O. C., Dahlke, H. E., Kaplan, R. E., and Van Houten, J. J., "Analytical and Experimental Studies of Weapon Muffling," LTV Research Center Report 0-71200/7TR-123, August 1967.

²Fansler, K. S., and Lyon, David H., "Attenuation of Muzzle Blast Using Configurable Mufflers," ARBRL-TR-2979, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, January 1989. (AD A206565)

³Davis, D. D., Stokes, G. M., Moore, D. and Stevens, G. L., "Theoretical and Experimental Investigations of Mufflers, with Comments on Engine Exhaust Muffler Design," NACA Report No. 1192, 1954, pp. 829-875.

⁴Whitham, G. B., "On the Propagation of Shock Waves Through Regions of Non-Uniform Area of Flow," *Journal of Fluid Mechanics*, Vol. 4, 1958, pp.337-360.

⁵Shapiro, A. H., "The Dynamics and Thermodynamics of Compressible Fluid Flow," Ronald Press Company, New York, 1953.

⁶Cooke, C. H. and Fansler, K. S., "A Mathematical Model of Early Time Blast Attenuation For One-Chamber Axisymmetric Mufflers," *Journal of Mathematical Computational Modelling*, Vol. 10, No. 5, pp.341-347, 1988.

⁷Mori, Y., Hijikata, K., and Shimizu, T., "Attenuation of Shock by Multi-Orifice," *Proceedings of the 10th International Shock Tube Symposium*, Japan, 1975.

⁸Smith, F., "A Theoretical Model of the Blast from Stationary and Moving Guns," *First International Symposium on Ballistics*, Orlando, Florida, 13-15 November 1974.

⁹Fansler, K. S., "Dependence of Free Field Impulse on the Decay Time of Energy Efflux for a Jet Flow," *The Shock and Vibration Bulletin*, Part 1, published by The Shock and Vibration Center, Naval Research Laboratory, 22-24 October, 1985, pp. 203-212.

¹⁰Heaps, C. W., Fansler, K. S., and Schmidt, E. M., "Computer Implementation of a Muzzle Blast Prediction Technique," ARBRL-MR-3443, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, May 1985. (AD A158344)

¹¹Cooke, C. H. and Fansler, K. S., "Numerical Simulation of Silencers," *Proceedings, 10th International Symposium on Ballistics*, San Diego, CA, 27-28 October 1987.

analysis of a small one-chamber muffler attached to the 25 mm M242 cannon. The results of the simulations are clearly portrayed in graphical form whereas the internal flow is difficult to observe experimentally. In the present work, a numerical scheme was adapted to the CRAY XMP-48 computer and used to simulate an experiment with a multi-chambered muffler of large bore volume, approximately nine gun volumes in size. The calculation continued for 16ms, at which time emptying of the muzzle was almost completed. An experiment was performed to compare with the numerical method and to give further insight into the flow processes internal to the muffler.

The numerical scheme used in this investigation evolved from a method devised by Harten¹² that solves the Euler equations of compressible flow in one dimension and is total-variation-diminishing (TVD), second-order-accurate and upwind-biased. Strang's operator splitting technique¹³ permits Harten's method to be applied to higher dimensional problems, such as arise in axisymmetric flow. Source terms may also be incorporated.¹⁴ Second-order schemes are perhaps optimal, in terms of the amount of computational effort required to implement an operator splitting of a given order of accuracy. In the absence of source terms, second-order schemes require a minimum of three operator applications per step to preserve second-order accuracy; whereas, for third-order accuracy to be preserved using fractional step splittings with positive fractional steps, no splitting having less than eight factors can exist.¹⁵ This represents minimally a three-fold increase in work for an increase of one in order of accuracy.

This report details the study of muffler internal flow by use of the numerical technique. Comparisons are made between experimental and calculated pressures at selected locations. In addition, pressure, density, Mach, and entropy contours are obtained at selected times, in order to analyze and understand the flow processes occurring in mufflers.

II. Cannon and Muffler Description

A schematic of the muffler is shown in Figure 1. The hole diameters of the baffles are 1.14 calibers. This muffler is outfitted with gages to record internal pressures. The gage identification numbers increase downstream from the muzzle, with the muzzle gage being designated as G1. Their positions are clearly shown in the later figures.

The bore length of the cannon is 80 calibers. The ammunition used was the M793 projectile. Muzzle exit flow values at time zero are:

$$p_e = 33.4 \text{ MPa}, \quad V_e = 1050 \text{ m/s}, \quad M_e = 1.52.$$

Here p_e is the pressure, V_e is the projectile velocity, and M_e is the Mach number of

¹²Harten, A., "High Resolution Schemes for Hyperbolic Conservation Laws," *Journal of Computational Physics*, Vol. 40, 1983, pp. 357-393.

¹³Strang, G., "On the Construction and Comparison of Difference Schemes," *SIAM Journal of Numerical Analysis*, Vol. 5, No. 3, September 1968, pp. 506-517.

¹⁴Cooke, C. H., "On Operator Splitting of the Euler Equations Consistent with Harten's TVD Scheme," *Numerical Methods for Partial Differential Equations*, John Wiley and Sons, Inc., New York, 1985.

¹⁵Cooke, C. H., McMorran, A. G., and Lowe, Stephen A., "On the Non-existence of Few Factor, Higher-Order Accurate, Fractional-Step Operator Splittings For Hyperbolic Systems of Conservation Laws," 11th AIAA Symposium on Numerical Fluid Dynamics, Williamsburg, Virginia, May 29-June 2, 1988.

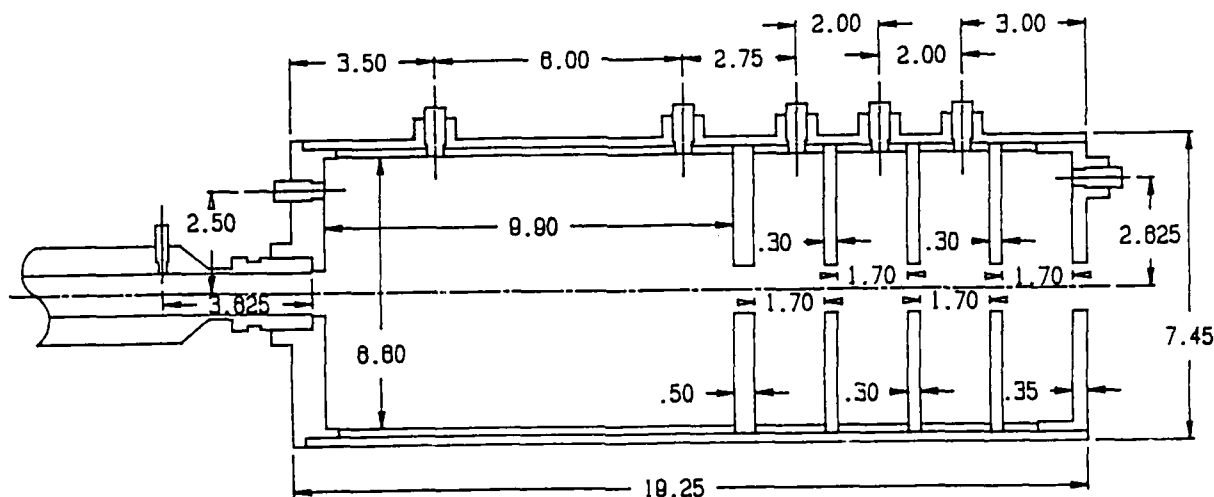


Figure 1. Schematic of Muffler Device.

the exit flow. In previous experiments, the propellant gases appeared to burn within the muffler. Before firing, both the barrel and muffler were purged with the nitrogen gas to inhibit burning. Three shots were fired to check for repeatability and obtain representative values at the pressure probes.

III. Simulation Conditions for the Muffler

In accordance with the practice in experimental work of referring to locations at which pressure histories are measured as probe positions, numerically calculated pressure histories will be referred to as numerical probe data. Numerical probes were placed at the same locations as for the experiment and also on the centerline at all baffle positions. Energy efflux values were also recorded at muzzle exit and at the projectile holes for every baffle.

Flow in the bore was initialized with a Lagrange model;¹⁶ thereafter, in-bore flow was updated with a one-dimensional numerical scheme. The projectile residence in the muffler was not simulated since the projectile would affect the flow only for very early times and then only minimally. In fact, the projectile will leave the muffler exit hole well ahead of any propellant gas. At time zero, the back of the projectile, if present, would clear the muzzle exit.

The computation proceeded for 16000 time steps, or roughly 16ms of time evolution for the physical problem. A grid of 21 points per caliber was employed. Other investigations

¹⁶Corner, J., "Theory of the Interior Ballistics of Guns," John Wiley and Sons, Inc., New York, 1950.

of gun blast problems have successfully used a more sparse grid point density.¹⁷

IV. Comparison of Numerical Results with Experiment

In this section, the muffler simulation results are compared with experimental data. As mentioned, the original data variation from shot to shot could be partially caused by the mixing of the propellant gas with the ambient air. The mixing was reduced by purging the muffler and cannon with nitrogen before each shot. Figure 2 shows the variation from shot to shot for the third gage, which is designated as G3. The differences between the pressures become greater at the larger times. Figure 3 shows the corresponding shot-to-shot variation for G7. The variation from shot to shot tended to increase for the downstream chambers.

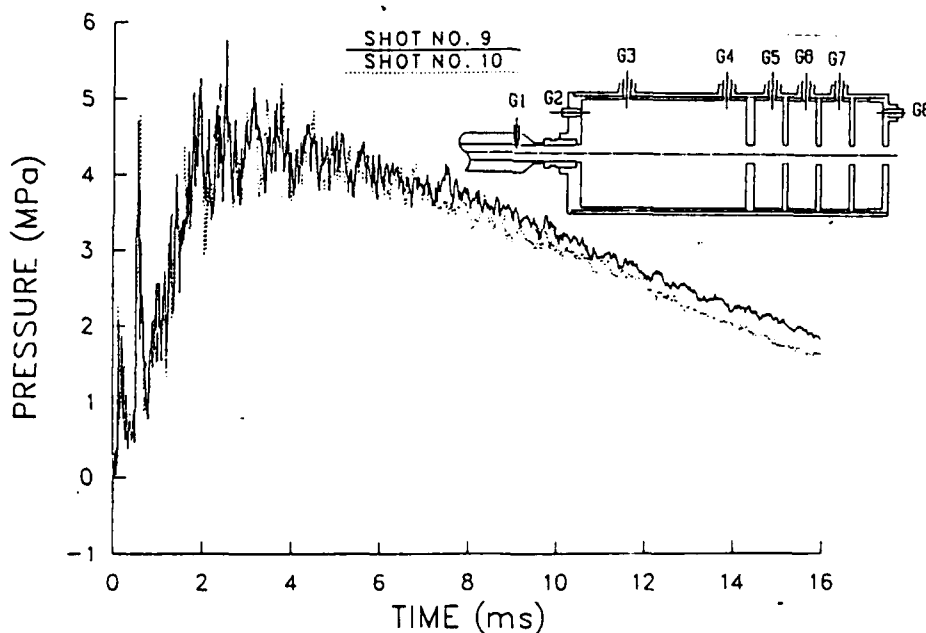


Figure 2. Shot to Shot Comparison, Gage No. 3.

Figure 4 shows the comparison between experiment and simulation for G3. Initially, the agreement is good except for the larger oscillations of the simulation. However, the calculated levels are lower for the later times and then converge toward the experimental values. The oscillations for both the experiment and simulation die out in a similar way, although the oscillatory character of the experimental data is more complex. The period of the oscillation for the simulation is the time for a wave to move from the periphery to the center and back again if the speed of sound were approximately 750 m/s, which

¹⁷Buell, J. C. and Widhopf, G. F., "Three-Dimensional Simulation of Muzzle Brake Flowfields," AIAA Paper 84-1641, June 1984.

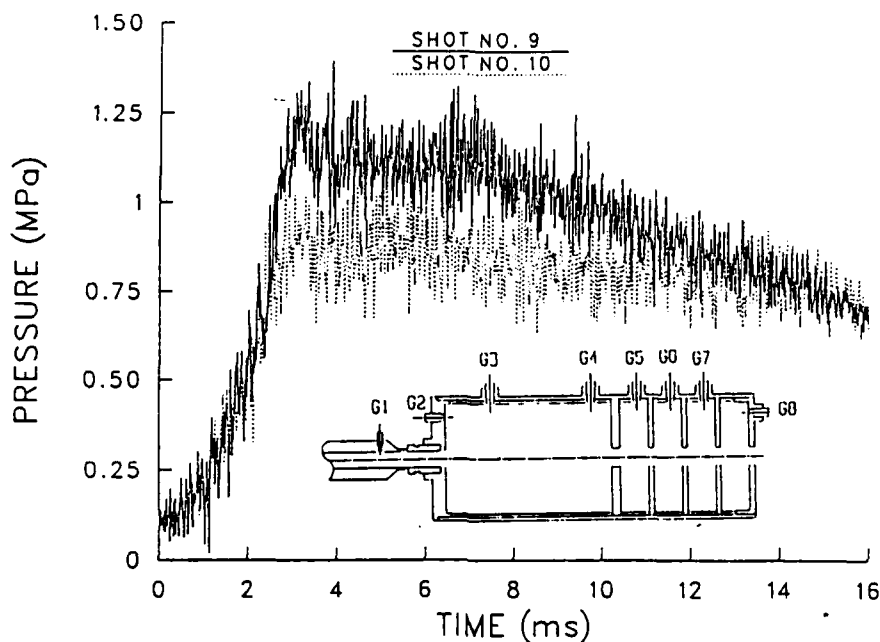


Figure 3. Shot to Shot Comparison, Gage No. 7.

agrees with calculated values obtained from interior ballistics.¹⁶ The experimental data also display such waves but they appear to die out more quickly and are partially obscured by other oscillatory waves. Figure 5 shows a comparison for G4, the gage forward of G3 but also in the inlet chamber of the muffler. In contrast to Figure 4, the simulated pressures are greater than the experimental values after 2ms. Again, the oscillatory waves for the experiment are more complex than for the simulation. Some of these waves may be created by turbulence initiated by burning reactions, which are discussed below in more detail. Of course, turbulence or burning reactions are not addressed with the simulation method.

For the experiment, the largest shot-to-shot variations occurred for the chambers nearest the muffler exit. Figure 6 shows that the differences between simulation and experiment are also larger. At gage 8, as shown in Figure 7, the experimental values are markedly larger than the simulation results. The oscillations persist in the experiment, whereas the calculated oscillations damp out almost completely by 4ms. More air may have remained in the chambers near the muffler exit and reacted with the fuel-rich propellant gas, thus raising the pressure and generating pressure waves. Also, the simulation does not model turbulence. For the gage positions nearest the muffler exit, the shot-to-shot variation is so large that it is difficult to meaningfully compare the experiment with the computational scheme. Nevertheless, comparison with experiment for early times and for the chambers nearest the muzzle yield encouraging agreement. It will be assumed that for purposes of analysis the computational method portrays the general flow picture for propellant gas that would not burn while passing through the muffler.

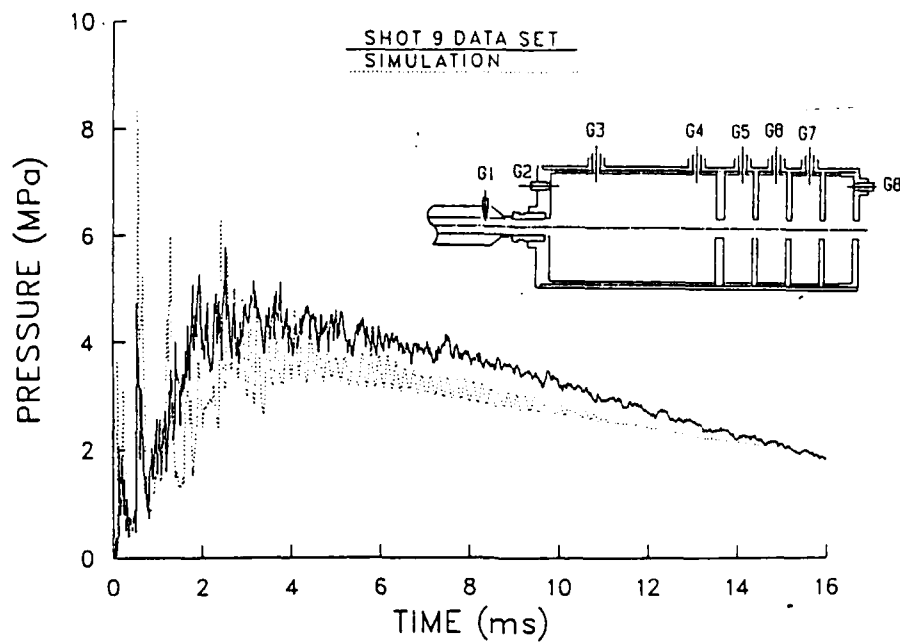


Figure 4. Comparison of Simulation with Experiment for Gage No. 3.

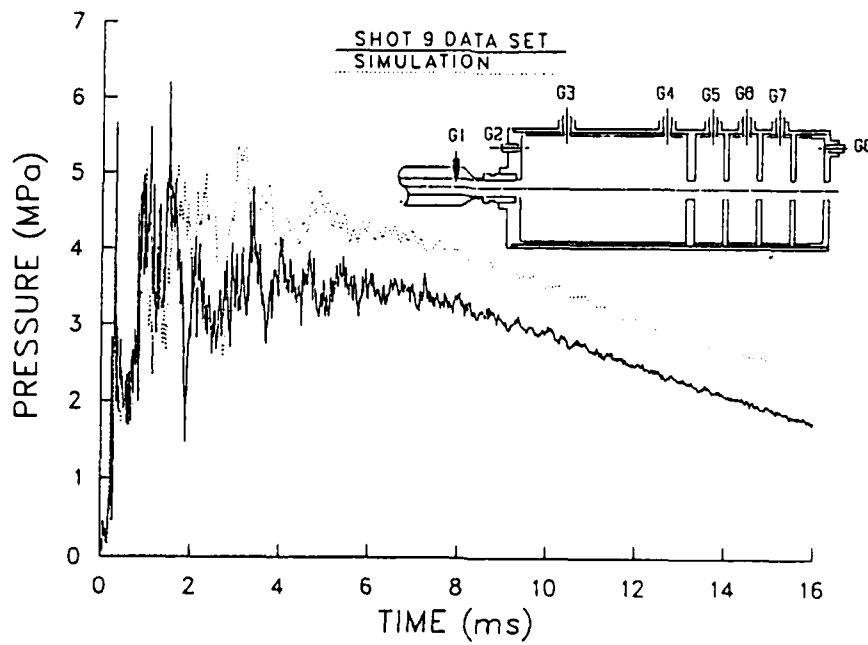


Figure 5. Comparison of Simulation with Experiment for Gage No. 4.

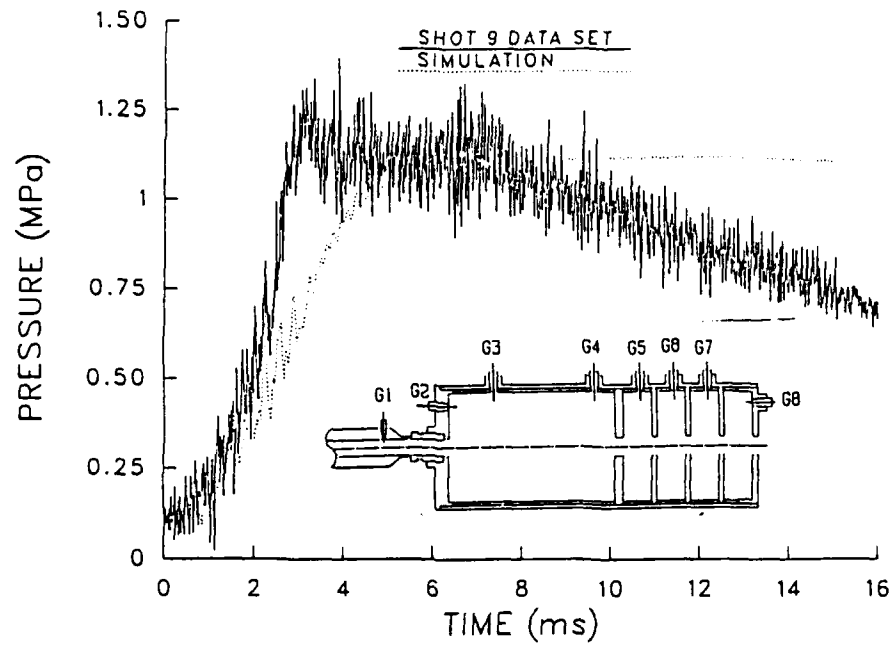


Figure 6. Comparison of Simulation with Experiment for Gage No. 7.

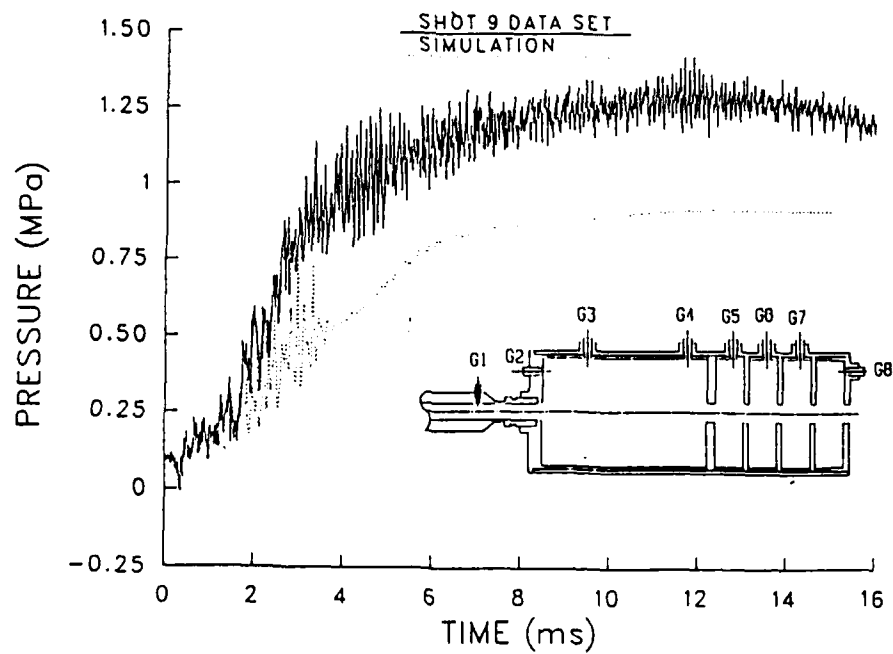


Figure 7. Comparison of Simulation with Experiment for Gage No. 8.

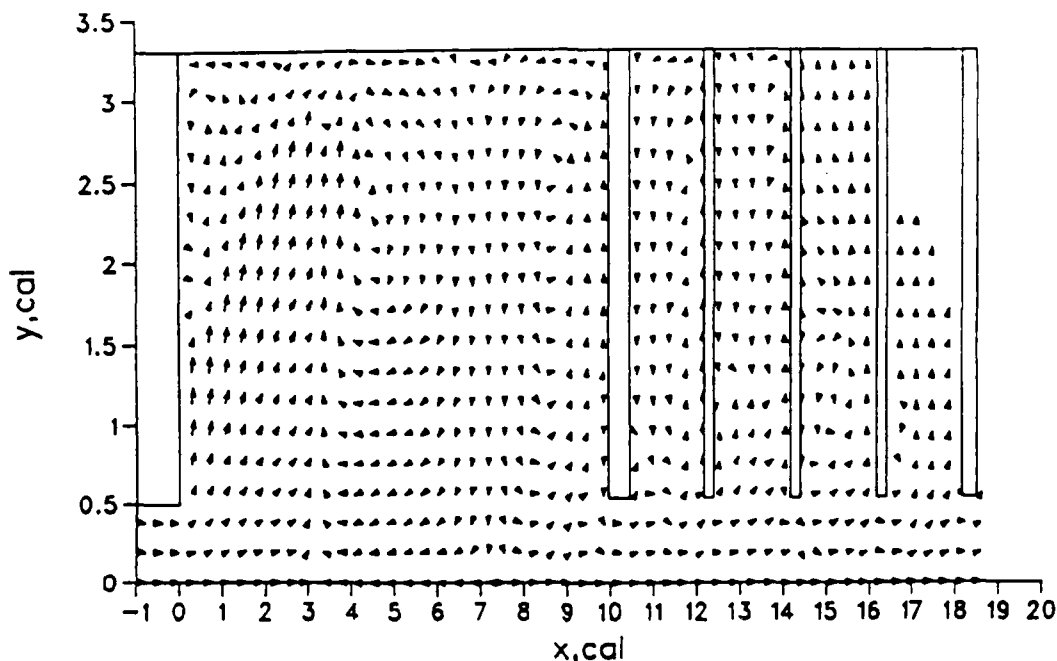


Figure 8. Velocity Vector Plot, 0.5ms.

V. Simulation Results and Discussion

Pressure, density, Mach, and entropy contours were obtained for various times during the simulation. Velocity vector plots were also made for the corresponding times. In Figure 8 the velocity vector plot is shown at 0.5ms. For the same time, the Mach contours in Figure 9 show the shock near the muzzle moving toward the muzzle after the inward facing shock has interacted with the reflected shock from the first baffle. Shocks are standing at the second, third, and fourth baffles. The shock at the second baffle is not as pronounced as for the next downstream baffle, possibly because the pressure in the first small chamber is high enough to inhibit the expansion of the jet coming from the entrance chamber. The entropy contours, displayed in Figure 10, also show the flow going through an oblique shock near the upper left corner of the inlet chamber and then forming a shear layer and vortex. The entropy contours show the extent of the shock processing for the flow. The clear space in the second, third, and fourth chambers is occupied by air.

In Figure 11, the velocity vector plot is shown for 1ms. Figure 12 shows the Mach contours for the same time, while Figure 13 shows the corresponding entropy contours. Shocks are standing upstream of the second, third, and fourth baffles. A weak shock appears to stand upstream of the exit baffle but the corresponding entropy plot does not confirm this. The complexity of the flow history is revealed by the convoluted patterns.

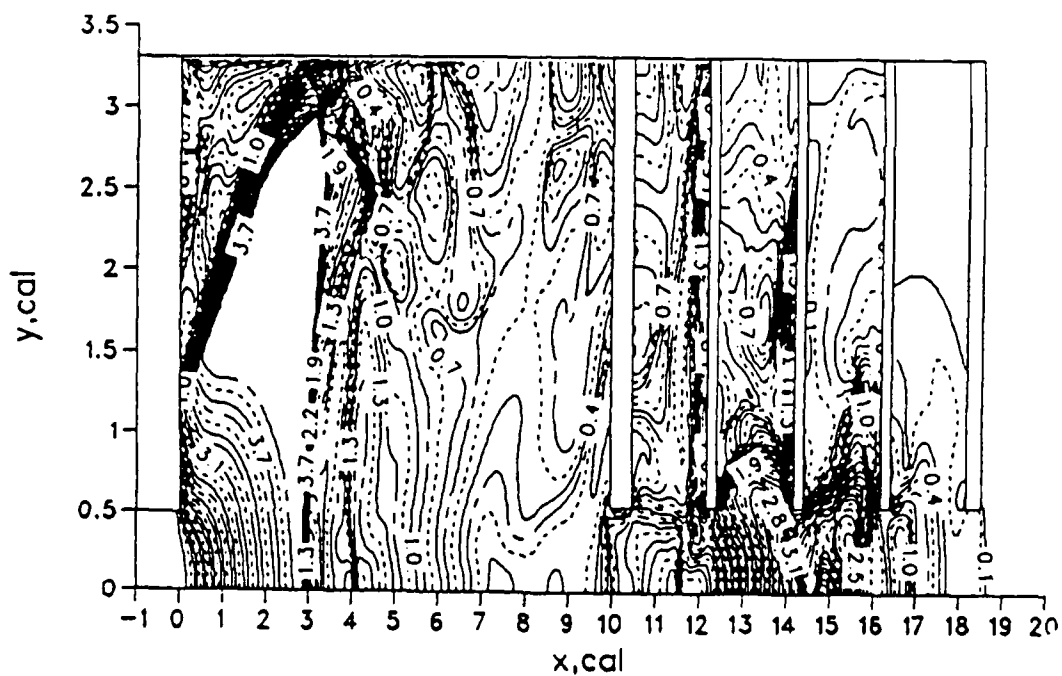


Figure 9. Mach Contours, 0.5ms.

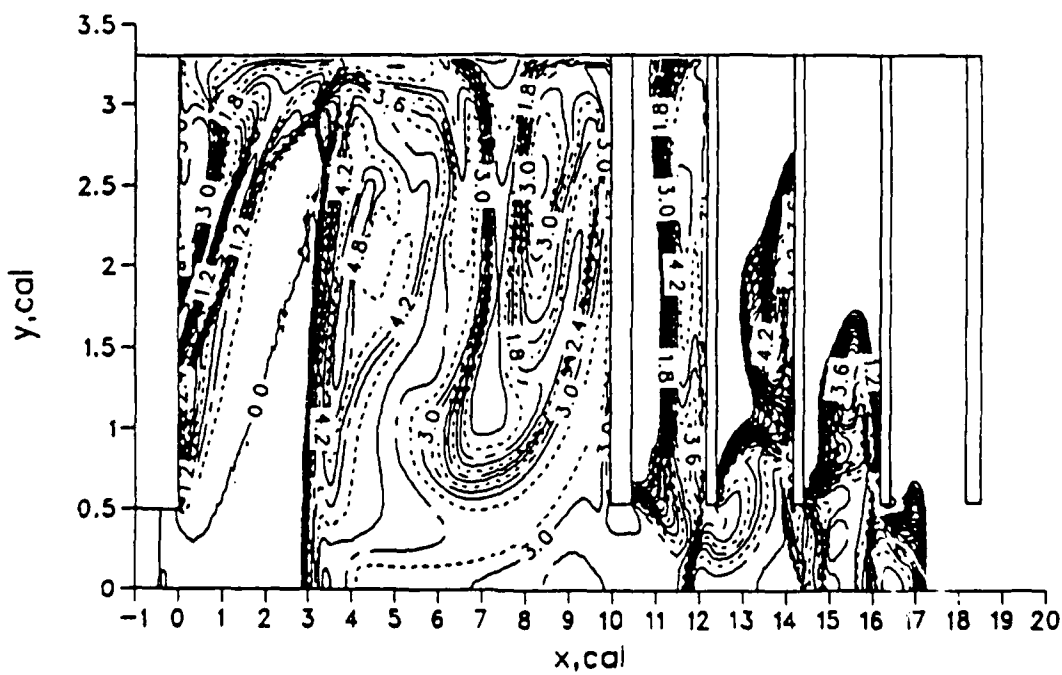


Figure 10. Entropy Contours, 0.5ms.

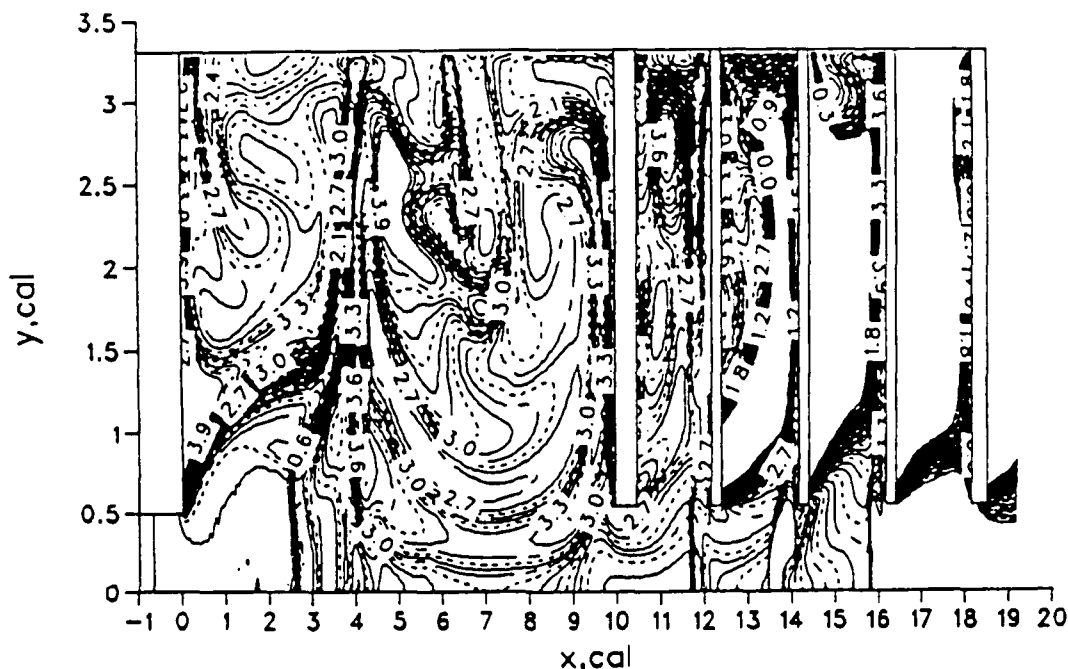


Figure 13. Entropy Contours, 1.0ms.

Figure 14 shows the density contours for 3ms, Figure 15 shows the corresponding Mach contour plots, while Figure 16 shows the entropy contour plots. These plots show that shocks are standing at the second, third, and fifth baffle projectile holes. The fluid in each chamber is vigorously rotating and as it nears the axis it turns and flows in the muffler exit direction. Although a vector plot was not made for this time, the contour plots show that the propellant gas flowing from the muzzle is pushing past the gas that exited into the chambers much earlier and is exiting from the muffler ahead of the gas that was originally processed with strong shocks. These propellant gases with less entropy have cooled by performing work and expanding. The energy efflux through each projectile hole can be expressed as

$$\frac{dE}{dt} = \frac{p_e u_e}{\gamma - 1} \left[1 + \frac{\gamma(\gamma - 1)}{2} M_e^2 \right] A_e. \quad (1)$$

Here, u_e is the mean velocity through the projectile hole, γ is the specific heat ratio, and A_e is the area of the projectile hole. When pressures in a chamber approximately equalize, the lower entropy gas passing through the projectile holes will have lower temperatures, which implies lower values for sonic velocities. The sonic velocity is identical to u_e for the times of interest. A well-designed muffler should preferentially act to pass the lower entropy gases as the energy efflux at the muffler exit hole is peaking.

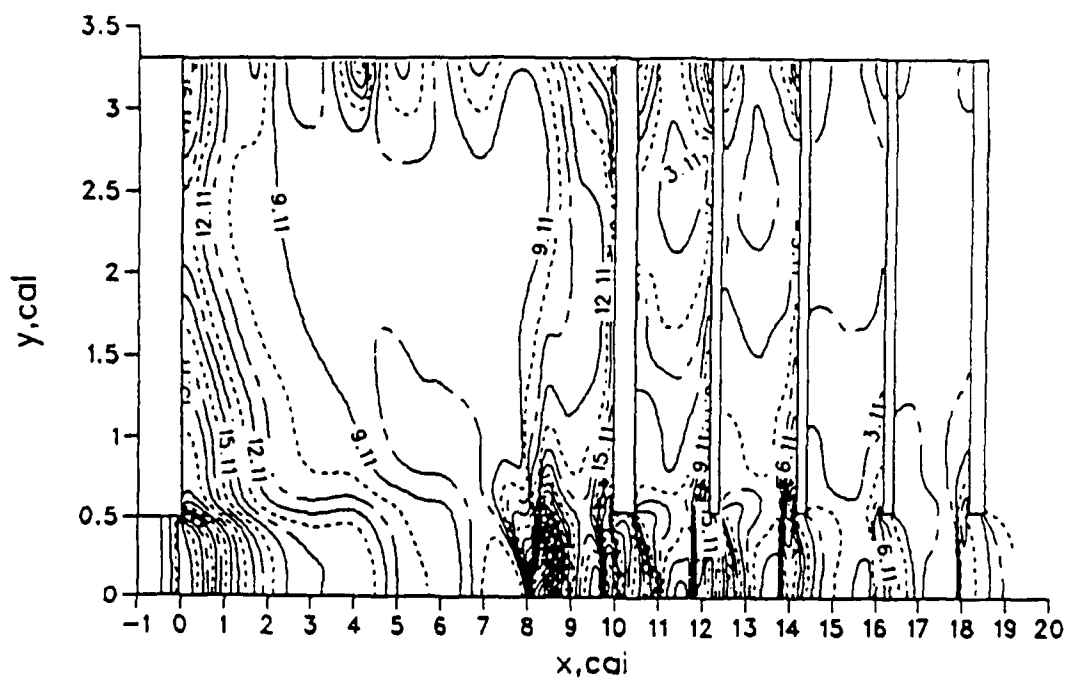


Figure 14. Density Contours, 3.0ms.

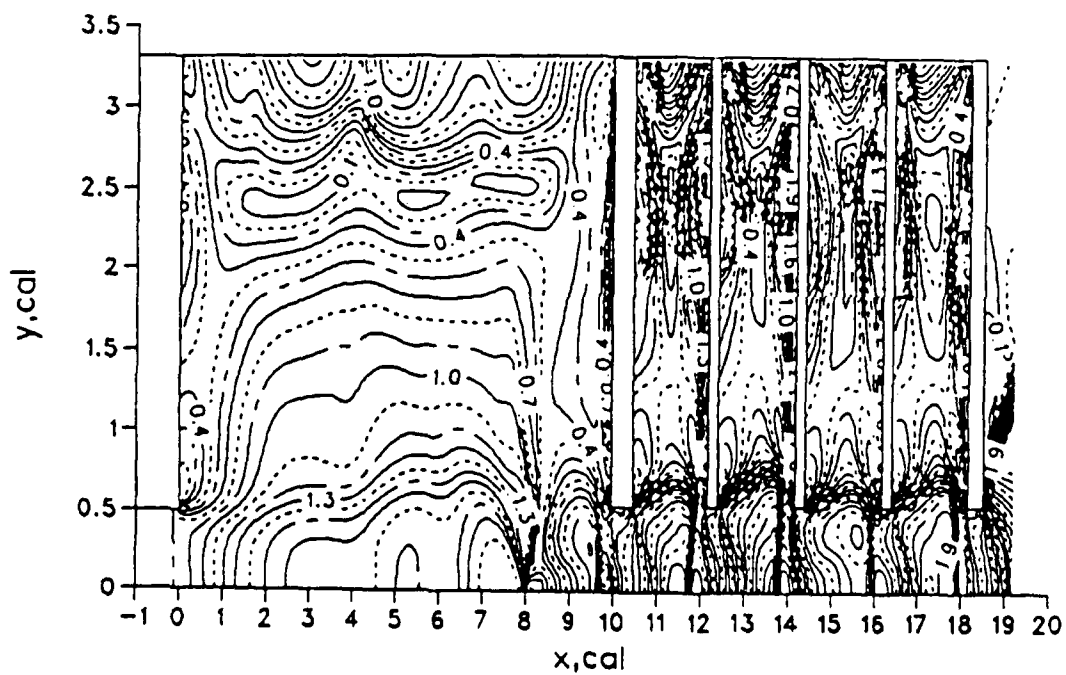


Figure 15. Mach Contours, 3.0ms.

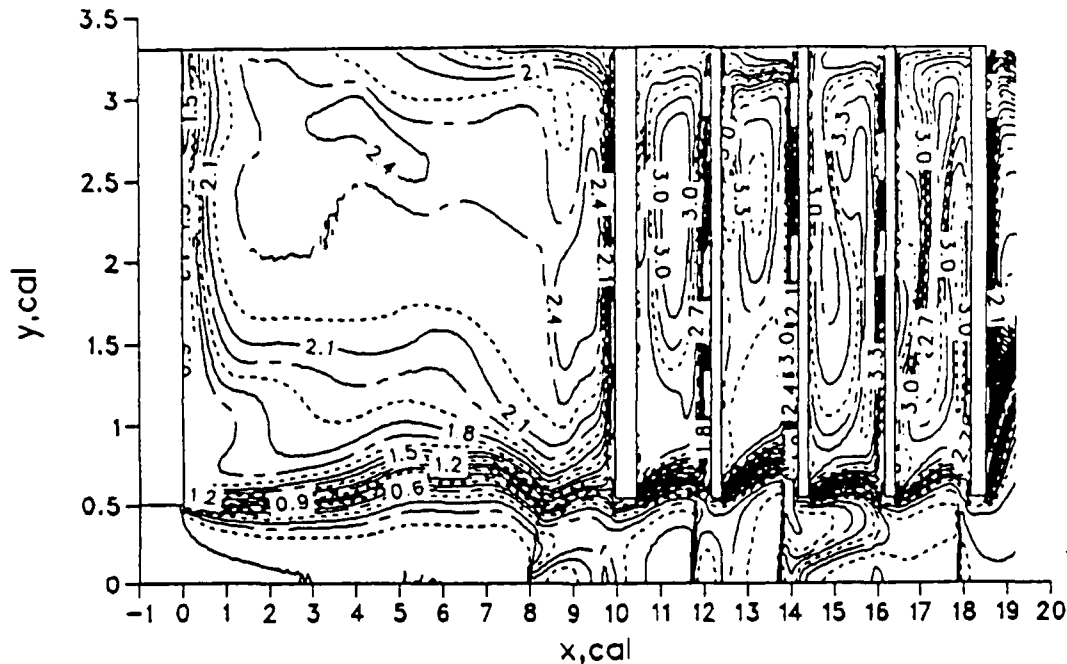


Figure 16. Entropy Contours, 3.0ms.

Figure 17 shows the simulated pressure histories at four gage positions inserted into the cylinder side and at the gage located on the muffler exit baffle. The pressures on each successive downstream baffle are lower and the amplitudes of oscillation also diminish for each successive downstream baffle. The inlet chamber's largest oscillations are connected with shock waves which are primarily axial in character. Radial waves are superimposed on these larger waves. The oscillatory waves in the next chamber appear to be driven by the waves from the inlet chamber. Figure 18 shows the simulated Mach number history along the axis at the gun muzzle and at the back or upwind surface of each baffle. Although unlabelled, it is obvious that the solid curve starting at a Mach number greater than one corresponds to the Mach number history at the muzzle. For the early flow, the severe pressure waves are moving the location of the sonic point back and forth across the simulated pressure probe position, thus causing the Mach number values to oscillate strongly. After 3ms, the calculated values are above sonic values during the period of interest. These results indicate that the flow is sonic at some axial location in each projectile hole. The jet flowing from each projectile hole drives the flow into the following projectile hole. The excess pressure on the upstream surface of the baffle at the projectile holes accelerates the impinging gas outward and along the upstream side of the baffle surface. At later times, as the pressure ratios for successive downstream chambers become smaller, the jet expands less and the flow channels through the projectile holes of the downstream baffles, with sonic conditions in each projectile hole.

Figure 19 shows the simulated energy efflux history through the baffle projectile holes. The original data was processed to reduce the wave amplitudes and show a clearer picture of the trends. For large pressure ratios and for the baffle distances shown here, the energy

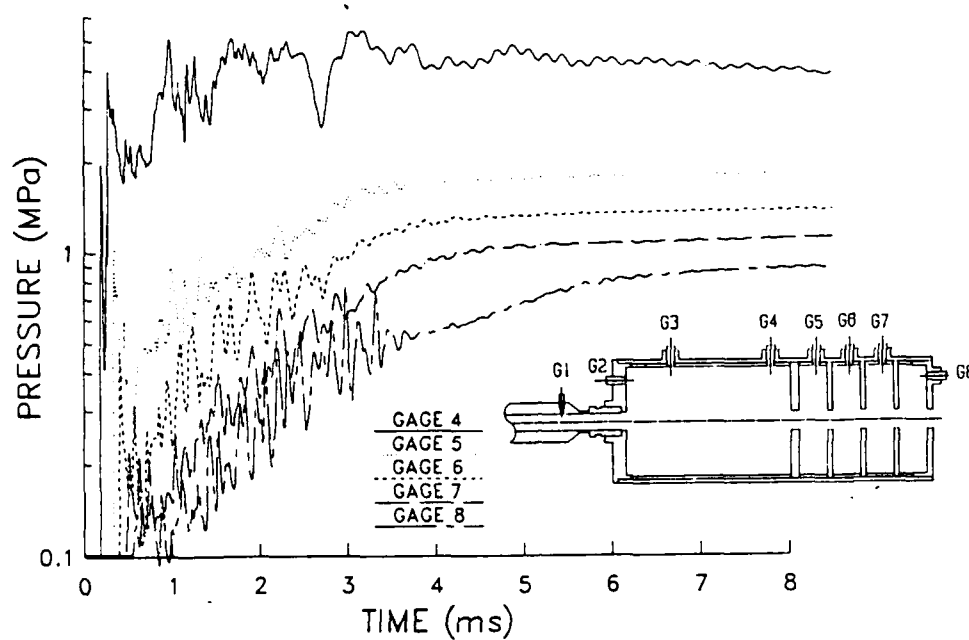


Figure 17. Simulation Pressure Comparisons.

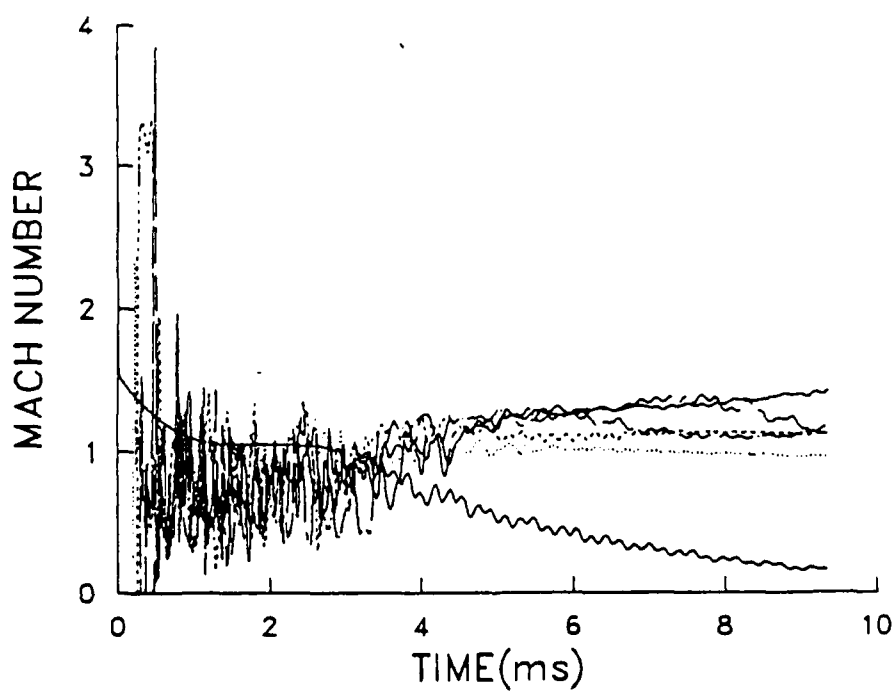


Figure 18. Mach Numbers on the Axis at the Muzzle and Entrance to Baffle Projectile Holes.

efflux should be almost ten times that of the next downstream hole.¹⁸ Such large pressure ratios occur here for very early times but then decline. At later times when the energy efflux maxima occur, the energy efflux ratios for adjacent baffles are almost constant in value. Although Figure 17 shows that only the inlet chamber has a clear pressure maximum for the times shown here, all the chambers exhibit clear maxima for energy efflux values. This occurs because, for later times, the cooler gas from the emptying barrel is preferentially passing through the exit hole of the entrance chamber without a large amount of shock processing. The shocks standing before each baffle are also becoming weaker and, before the maximum is reached, the stagnation pressure increases as the entropy change through the shocks decreases. Although the pressures at sonic conditions are slowly increasing, the sonic velocities are decreasing. If u_c decreases rapidly enough, Equation 1 shows that the energy efflux will have a maximum value.

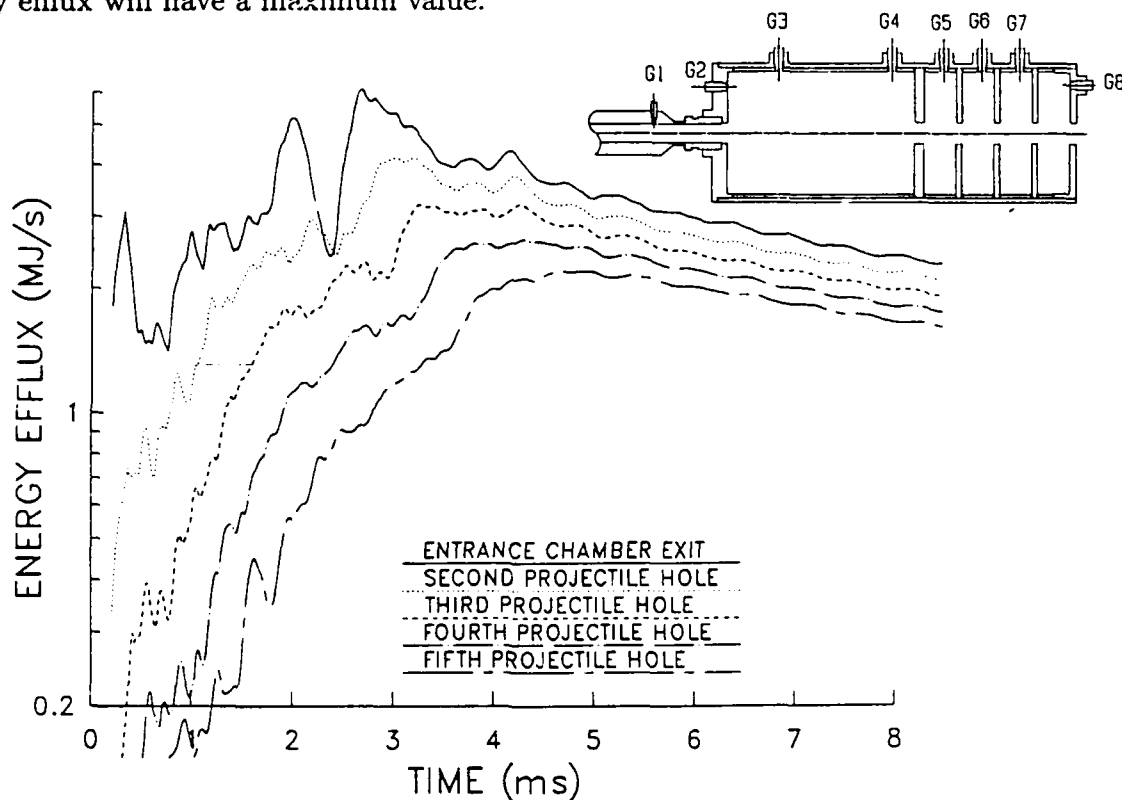


Figure 19. Energy Efflux through Baffle Projectile Holes.

The peak energy efflux values for adjacent projectile holes appear to have a constant ratio if the fluctuations are smoothed out. The existence of sonic conditions at all projectile holes implies that the flow in a downstream chamber does not affect the flow in an upstream chamber. If another identical chamber were added on, the energy efflux of the new exit hole would then be a certain fraction of the energy efflux from the present exit hole. Now, the peak overpressure level at a point in the muzzle blast field is proportional to a power of the peak energy efflux. Thus, the noise level attenuation in decibels would be a linear function of the number of chambers for the muffler. This conclusion agrees with the experimental results of Bixler et al.¹

¹⁸Fansler, K. S., "A Simple Method for Predicting Muzzle Brake Effectiveness and Baffle-Surface Pressure," ARBRL-TR-02335, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, June 1981. (AD A102349)

The noise attenuation for the simulated muffler is calculated to be approximately 18 dB if the peak energy efflux values are used.¹⁰ In the near field, the measured value was 21 dB at 90 degrees to the boreline. Although attenuation was not measured in the far field, the measured values are generally smaller than obtained for the near field. The good agreement indicates that the peak value of the energy efflux from the muffler exit hole may be used in predicting the noise attenuation performance of a muffler. Simulation of the muffler's external flow field with a rapidly executing numerical code¹⁹ could be used to study how the exit energy-efflux history determines peak overpressure and other parameters of interest.

The flow through the closely spaced holes, as discussed above, differs from that for successive orifices separated so that the jet flow is not impinging on baffles. Huseman²⁰ has developed and validated a code for treating such a flow. Simplifying assumptions are no chemical reactions and instantaneous mixing of incoming gases, resulting in mass-averaged properties within each volume. For application to the present muffler and conditions, the chambers are treated as being sequentially connected with no heat transfer to the chamber walls. Figure 20 shows the pressures calculated in each chamber. The pressures in the muffler's smallest chambers rise much slower than the pressures calculated by the more detailed numerical simulation, Figure 17.

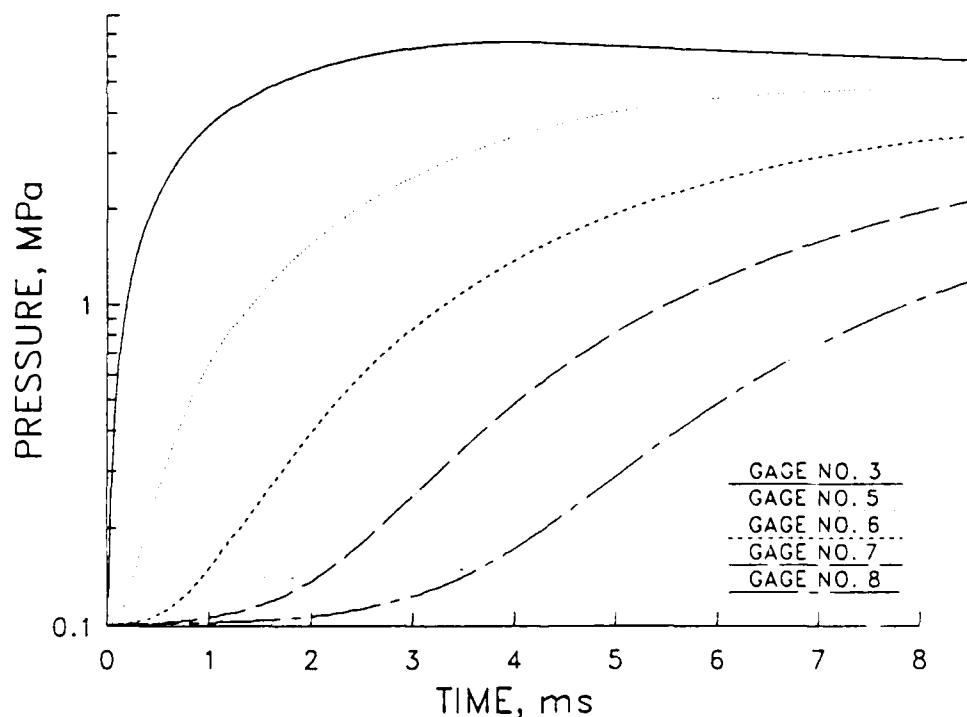


Figure 20. Pressures in Muffler Calculated with a Connected Cavities Model

Although not shown here, the pressure values in the exit chamber eventually exceed the detailed simulated pressures by more than a factor of two. These results indicate that

¹⁹Erdoes, J. I. and DelGuidice, P., "Gas Dynamics of Muzzle Blast," *AIAA Journal*, Vol. 13, August 1975, pp. 1048-1055.

²⁰Huseman, P. G., "A Gas Dynamics Model for Connected Compartments," AIAA Paper 84-1728, June 1984.

the muffler with closely spaced baffles is a more efficient noise attenuator than a muffler designed to correspond closely to the model that assumes instantaneous mixing with mass averaging.

Wire screens or materials with high flow resistance in a muffler have been used extensively to improve muffler performance.¹ The use of a screen would inhibit the swirling motions of the fluid in the muffler and the heavily shock-processed fluid with high entropy that is produced in the first part of the muffler-emptying process would tend to be pushed to the periphery of the muffler. These gases would be the last to leave the muffler and would exhaust with a low energy efflux. When properly designed, the high-flow-resistance material would decrease the flow into the chambers which would initially increase the pressures in the chambers near the projectile holes, and enhance the flow rate from the muffler exit when the energy efflux level at the muffler exit is rising. The early enhanced exhaust of propellant gas can then reduce the maximum values for the energy efflux. Of course, the screen is very effective in reducing the energy in the hot gases, thus further enhancing the muffler performance.

VI. Summary and Conclusions

The operation of a multi-chambered muffler was investigated both by experiment and simulation. Pressure probes were inserted into the muffler to obtain the pressure history in each cylinder. Shot-to-shot repeatability was good except for the chambers located nearest to the muffler exit hole. Random occurrences of propellant burning could account for some of the poor shot-to-shot repeatability for the chambers nearest the muffler exit. Experiment and simulation were in general agreement, but more so at earlier times and for the chambers located nearest the gun muzzle. The differences are attributed to propellant reacting with air in the chambers, possible errors associated with the approximation of the initial in-bore gas-dynamic quantities, and to inviscid modelling of the flow instead of taking into account viscosity and turbulence.

Pressure, density, Mach, and entropy contours were obtained by simulation for times up to 3ms. Contours at later times are needed for a more complete analysis, particularly to study the shocks standing before the baffle projectile holes. The contours and numerical probes at the upstream sides of the baffles show that the flow is sonic through the projectile holes. This implies the flow independence of preceding baffles. The almost constant energy efflux ratios for successive chambers when efflux maxima occur, together with flow independence, further implies that the attenuation of the blast in decibels increases linearly with the number of baffles.

Since the peak value of the energy efflux from the bare muzzle determines the peak sound pressure level in the external flow field, perhaps the peak sound pressure level for the muffler might also depend upon the energy efflux from the muffler exit hole. When the simulated peak energy efflux is used with a prediction method, good agreement is obtained with experiment.

Both experiment and simulation show large pressure waves initially being generated

in the entrance chamber but decaying with time. Moreover, these waves attenuate as they travel toward the muffler exit hole. These pressure waves contribute negligibly to the peak value for the energy efflux from the muffler exit hole and thus have little influence over the noise attenuation values.

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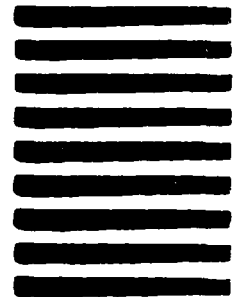


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